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14. ABSTRACT

This report results from a contract tasking Institute of Semiconductor Physics as follows: The contractor will investigate (experimentally and theoretically) the thermo-dynamical limitation for stability of the extra-thin monocrystalline Si films with different crystallographic orientation on different wafers produced by hydrogen transfer during the first year; will create XT Si layers on handle wafers with delta doped layer saturated and oversaturated by boron and germanium and investigate their properties during the second year; and form EXTF structures on a ceramics instead of semiconductor substrates. The objectives of this project are: the formation of extra thin (XT, 1 nm) and ultra thin (UT, 10 nm) single crystal (100), (110), and (111) silicon films with atomically flat interfaces with substrate (handle wafers based on different materials) by means of hydrogen induced transfer after the bonding of Si donor to handle wafers and investigation of basic processes, which determine the position of splitting plane for semiconductor donor wafer with decrease in hydrogen ion energy and transferred film thickness as well as; the formation of XT and UT single crystal Si films with atomically flat interface and surface using weak delta doped layer transfer technique and investigation of roughness evolution by AFM and SEM; and the formation of strained XTSF structures and investigation of quantum confinement and dopant distribution effects on two dimensional free carrier transport in XT and sXTSF test structures.

15. SUBJECT TERMS
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FINAL REPORT

Project-RUP1-1507-05 "Extra thin silicon film structures for post silicon microelectronics"

Introduction

The formation of heterostructures by the transfer of thin silicon films is based on the splitting effect of a top layer being over the hydrogen-supersaturated silicon region [1-5]. Usually, the thickness of the hydrogen-transferred silicon films is not below 500 nm [6-9]. It is limited by the condition to keep the high concentration of hydrogen within the ion-implanted silicon layer. It is necessary to form the microcracks at the required depth from the top silicon surface. However, as a rule, splitting takes place not in the maximum of hydrogen concentration but near the maximum of defect concentration. It is necessary to note, that real silicon surface is also a trap for both ion-implanted hydrogen and radiation defects. This means, that reduction of the hydrogen ion energy below a critical magnitude may result in gettering of hydrogen atoms by silicon surface and in prevention of the microcrack formation. Under these conditions, breaking up the transfer process takes place. In order to develop methods of the exfoliation of thin and ultra-thin silicon films, we suggest using the effect of boron atoms on the enhancement of the microcracks formation. This goal is motivated by the boron property as an effective getter for both radiation point defects and hydrogen atoms.

In the frame of the project, four kinds of studies have been carried out. In section "Task 1", the effect of boron on the formation of inner surfaces in hydrogen ion-implanted silicon was investigated. In section "Task 2", the structure of silicon films transferred from the boron doped silicon layers were examined. Theoretical models of the exfoliation process were reviewed in section "Task 3". Electrical measurements of the transferred thin silicon films were prepared in the frame of "Task 5".

Task 1. Investigation of inner surface formation process in the silicon crystals with delta doped semiconductor films irradiated by hydrogen with different energy.

Nucleation and growth microcavities and blistering processes in highly boron-doped silicon implanted with hydrogen ions were studied as a function boron atom concentration. Two kinds of boron doping have been used in these experiments. Namely, they are boron ion implantation and boron in delta-layers.

1.1. Nucleation and growth microcavities and blistering processes in the highly boron doped silicon.

In order to produce the highly boron doped silicon layers, the p-type, (100) oriented silicon wafers were implanted with B^+ ions at an energy of 300 keV to doses of 5×10^{15}, 1×10^{16} and 1.5×10^{16} cm^{-2}. Boron concentration in unimplanted samples was about 2×10^{15} cm^{-3}. The ion-implanted wafers were annealed at the temperature of 1075° C during 100 minutes. Then, boron doped silicon wafers were implanted with H_2^+ ions at an energy of 135 keV to dose of 2×10^{16} cm^{-2}. Ion implantation carried out through the protective thermally grown SiO_2 layer with the thickness of 100 nm. Finally, the samples treated at the temperature ranging from 200 to 800° C in nitrogen ambient. Boron profiles have been controlled by second ion mass spectrometry (SIMS) technique. Hall effect measurements, Rutherford backscattering (RBS) and channeling of He^+ ions at an energy of 1.4 MeV, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) methods were used to study of the electrical and structural properties of the produced layers.

Figure 1 shows boron profiles measured by SIMS from the silicon samples implanted with B^+ ions at an energy 300 keV to doses 5×10^{15} and 1.5×10^{16} cm^{-2} after annealing at $T_a =$
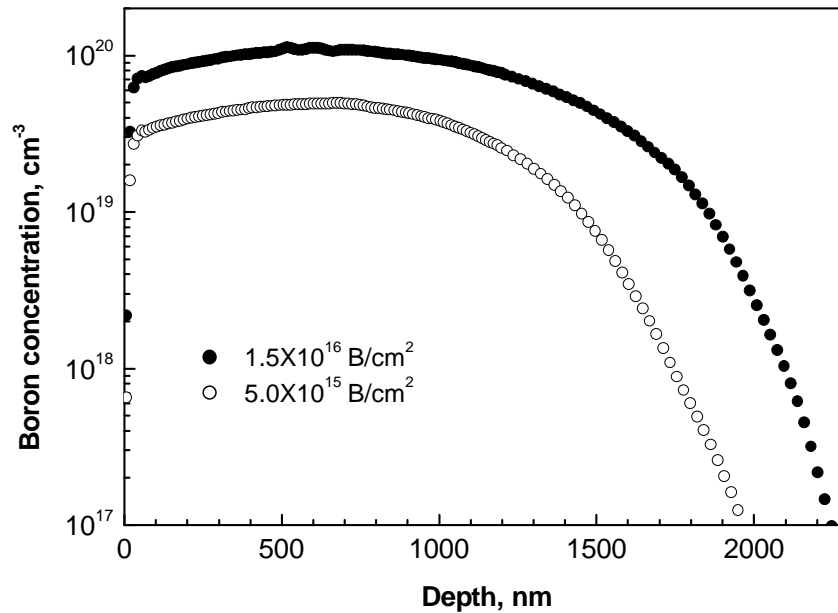

Figure 1. Boron profiles produced by the implantation of B^+ ions at an energy 300 keV to doses 5×10^{15} and 1.5×10^{16} cm^{-2} in silicon wafers and by subsequent annealing at $T_a = 1075^o$ C during 100 minutes in nitrogen ambient.
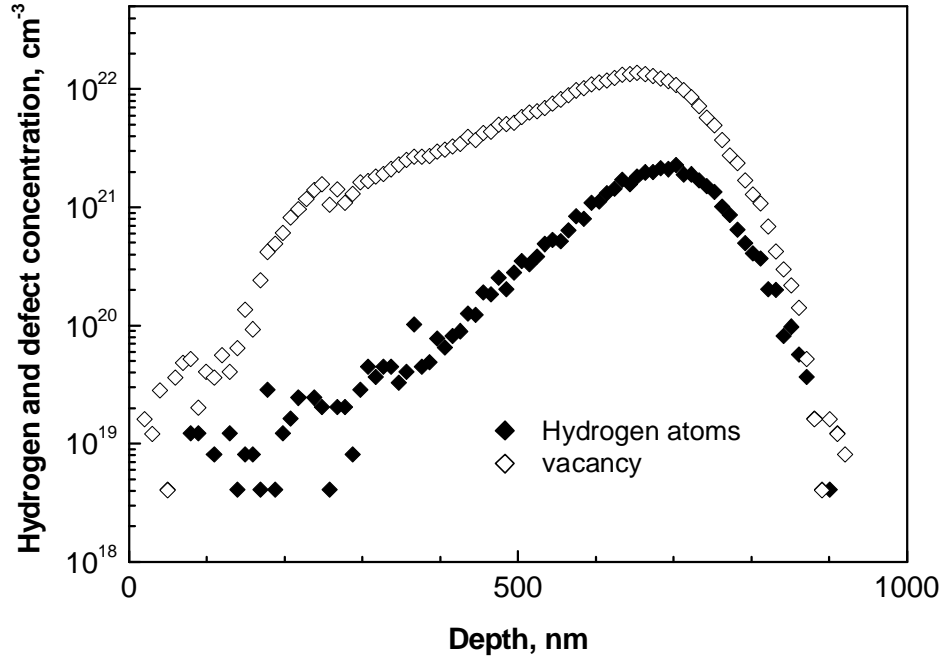
Figure 2. Hydrogen atom and vacancy profiles calculated by TRIM'95 program for H_2^+ ions implanted in Si at an energy of 135 keV to dose of 2×10^{16} cm^{-2}.

1075° C during 100 minutes. Maximum boron concentration in the layers was 3×10^{19} and 9×10^{19} cm^{-3}, respectively. The profiles of hydrogen and displaced atom obtained from the calculations by TRIM'95 program are presented in Figure 2. One can see, that both hydrogen atoms and defects produced as result of H_2^+ ion implantation are located within the highly boron doped layer.

Hall measurements show, that polarity of conductivity is dependent on the boron concentration. In the case of low boron concentration ($\sim 2 \times 10^{15}$ cm^{-3}), hydrogen irradiation results in modification of conductivity polarity from p- to n- type. This effect is stable under subsequent annealing within the temperature range 370 - 550° C, and is connected with the formation of thermo- and hydrogen donors. Annealing at the temperature higher than 550° C results in the reconstruction of boron electrically active concentration. It was observed, that p-type concentration was kept as the boron content in the samples increased to 10^{19} cm^{-3}. In the case of highly boron doped samples (10^{19} – 10^{20} cm^{-3}), no change in conductivity type under irradiation taken place. However, a part of electrically active boron decreased as the hydrogen dose grown. These results show, that interaction between boron atoms and radiation defects results in the formation of electrically inactive boron in silicon lattice. Figure 3 shows a dependence of the normalized hole concentration on the annealing temperature in silicon

samples containing 3×10^{19} cm^{-3} of boron atoms and implanted with different doses of hydrogen ions. Donor concentration was obtained to be dropt as annealing temperature increased to 250° C. This effect is produced by destruction of B-H-complexes. Dissociation of these complexes taken place at the temperature higher than 250° C. Next increasing in T_a results in reconstruction of the acceptor properties of boron atoms. Figure 3 demonstrates that acceptor concentration is lower for the samples implanted to higher hydrogen dose.
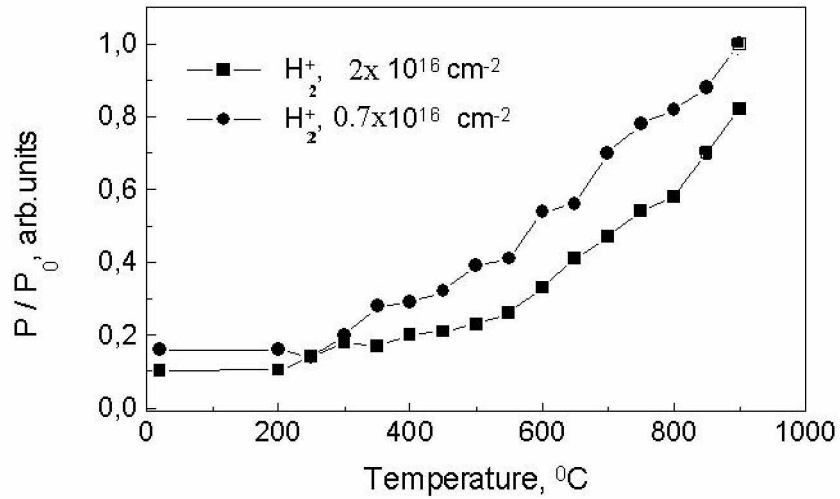

Figure 3. The normalized hole concentration as a function of annealing temperature in Cz-Si samples implanted with different doses of hydrogen ions. Initial boron concentration is 3×10^{19} cm^{-3}.

RBS and channeling methods are sensible to the point defects. Figure 4 shows RBS and channeling specters of silicon samples with the boron content ranging from 10^{15} to 10^{20} cm^{-3} after implantation of 2×10^{16} H cm^{-2}. In the case of highly boron doped silicon samples, figure 4 shows a decrease in the defect concentration near the ion projecting range R_p =750 nm in comparison with that obtained from the low doping samples. In the case of near-surface layers (channels 100-150), after hydrogen dose lower than critical dose required for blistering, RBS count was obtained the same as that both from virgin monocrystalline silicon and from the low boron doped layers. RBS count increased as boron concentration grown. The porous formation and respective deformation of silicon lattice are possible reasons of this effect. This supposition is confirmed with the results presented in figure 5. Thus, the results obtained from RBS and Hall measurements suggest that the boron-contained defects may provide for the microcavity nucleation both during hydrogen implantation and after subsequent annealing.
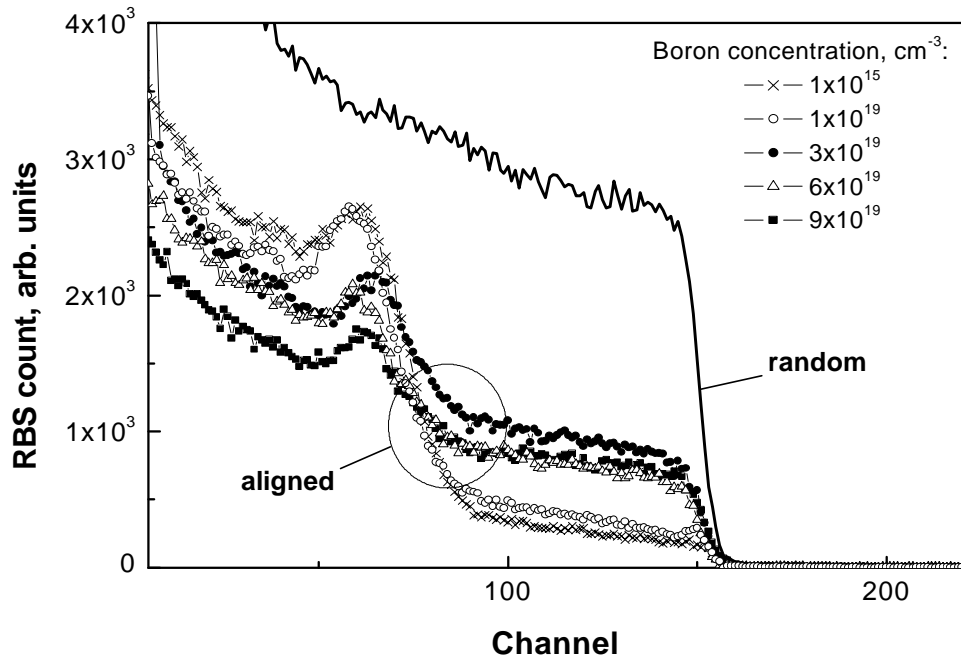
Figure 4. RBS and channeling specters from boron doped silicon with the concentration ranged from 10^{15} to 10^{20} B/cm^{-3} after implantation with H_2^+ to dose of 2×10^{16} cm^{-2}.
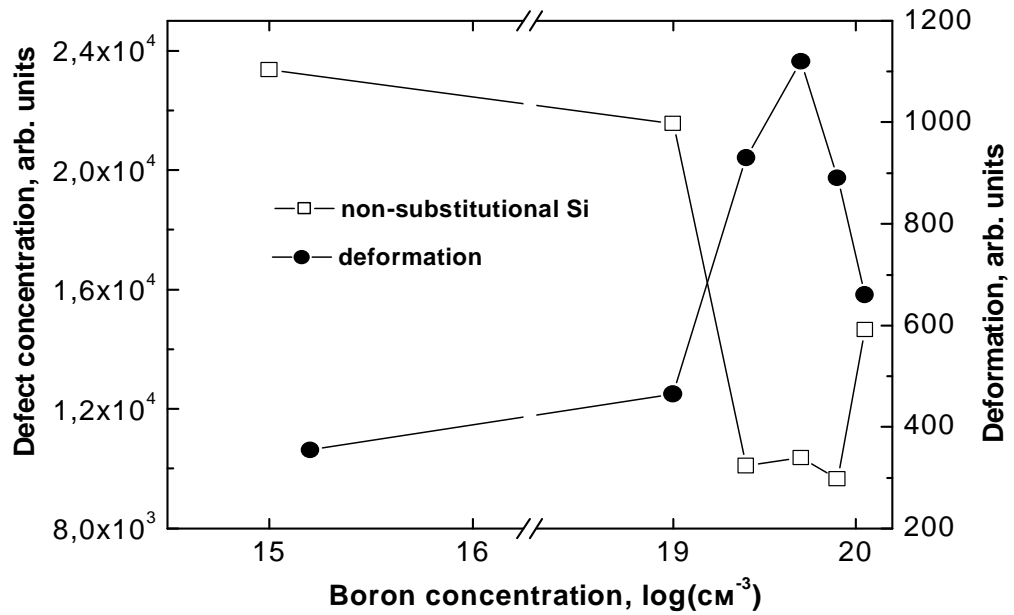
Figure 5. Concentration of the displaced Si atoms and deformation produced by blisters as a function of boron content.

In order to study the defects responsible for nucleation of blisters and voids, the structural investigations of the boron doped samples implanted with hydrogen ions were carried out by TEM and SEM methods. It was obtained, that a density of microcracks decreased in the highly boron doped samples according with these in the boron free silicon samples. Moreover, the plate-like defects are not observed from the highly boron-doped silicon layers implanted with hydrogen ions. These results suggest, that low concentration of the point defects in boron-doped silicon prevents from the formation of lengthy defects. As result, no molecular hydrogen binds on the microcrack edge takes place. It means, that hydrogenated of inner surface occurs. Thus, instead of microcracks, the boron-connected defect complexes produce a new kind of the blister nucleation centers. These are the micropores.
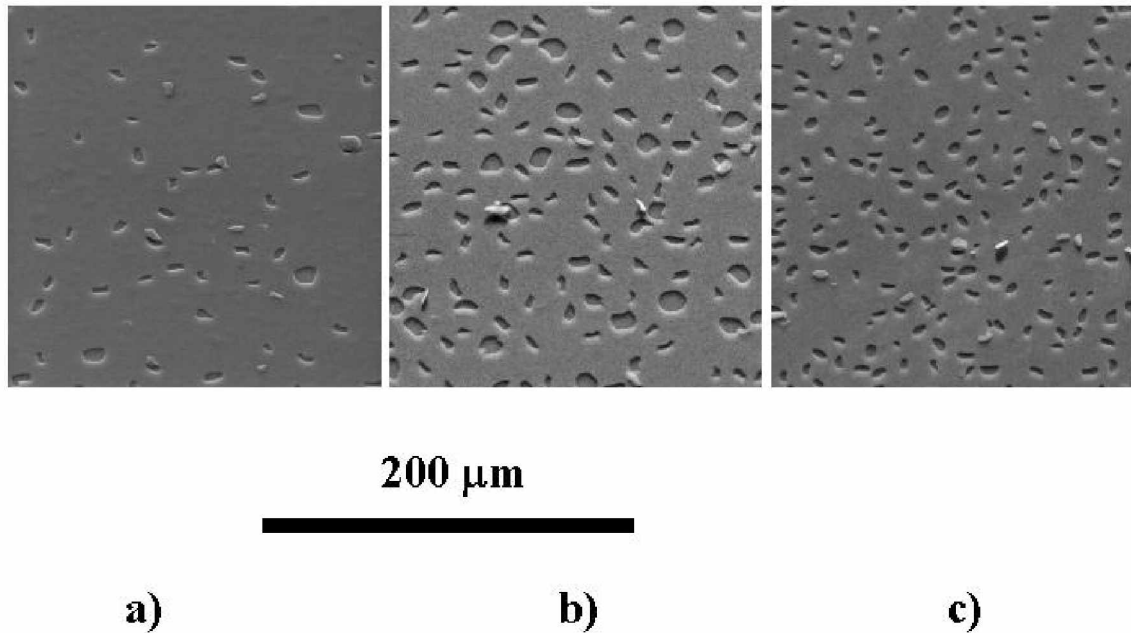

200 μm

a)   b)   c)

Figure 6. Scanning electron microscopy images of the boron doped silicon samples implanted to H_2^+ ions at an energy of 135 keV to dose of 2×10^{16} cm^{-2} after annealing at the temperature of 450° C for 1 hour. The boron concentration, cm^{-3}: (a) 2×10^{15}; (b) 6×10^{19}, and (c) 9×10^{19}.

Figure 6 shows scanning electron microscopy images of the 2×10^{16} H_2^+/cm^{-2} implanted samples as a function of boron concentration after finale annealing at the temperature of 450° C for 1 hour. As shown in the picture, increasing boron concentration from 2×10^{15} (Fig. 6a) to 9×10^{19} (Fig. 6c) cm^{-3} results in the growth of a density of blisters and in decreasing its dimensions.

These results suggest that the highly boron doped silicon layers contain the heterogeneous nucleation centers of high density.

1.2. Nucleation and blistering processes in silicon doped with boron delta-layer.

The p-type, 10 Ω cm, (100)-oriented silicon wafers were used as the substrates. Then, boron delta-layer was grown on the top silicon surface by the molecular-beam epitaxy (MBE) technique. Boron concentration in delta-layer was ranging between 6×10^{14} and 1.5×10^{15} cm^{-2}. Next, the boron-doped layer was covered again with silicon film. The thickness of the top silicon layer varied from 20 to 800 nm. The prepared structures were covered with thin protective silicon dioxide layer and then implanted with H$_2^+$ ions at an energy of 40-120 keV to a dose of 2×10^{16} cm^{-2}. Oxidation temperature was 1050° C. Under these conditions, the boron delta-layer diffused to the thickness of 10 - 30 nm with the bulk boron concentration ranging within (2-5)$\times 10^{20}$ cm^{-3}, respectively. Cross-sectional high-resolution microscopy (XTEM) was used to study the formation of microcracs and evolution of roughness of the inner surfaces. Infrared spectroscopy (IR) was employed to investigation of the boron atom effect on local stretch mode of hydrogen. With that end in view, two kinds of prisms were prepared. These prisms consisted of two bonded silicon wafers. One of these contained ultra thin boron layer with a thickness of 30 nm. Second ones were the prisms without boron. Infrared spectra were investigated as a function of the temperature and duration of subsequent annealing ranging within T = 200-650° C and t=5-120 min, respectively. A cross-sectional high-resolution microscopy image of structure implanted with H$_2^+$ ions at the energy of 100 keV is shown in figure 7. In this case, the ion range was close to the delta-layer position. Figure 7 shows the formation of the microcracks of about 500 nm long within the boron-doped region. This microcracks lie parallel to the top silicon surface.

Figure 8 shows the samples, containing boron delta-layer at the depth of 800 nm from the top silicon surface, after implantation of 100 keV H$_2^+$ ions. In this case, the distance between the ion range and boron delta-layer was about 300 nm. The formation of microcracks was studied as a function of subsequent annealing at the temperature of 350 and 450° C for 1 hour. It was obtained, that 350° C-annealing results in the formation of microcracks within both the hydrogen ion implanted region and boron-doped layer (see figure 8a and 8b). Figure 8b shows the same samples lopsided to 10°. It is clear, that the plate-like defects formed in the hydrogen ion implanted region only. In the area of the boron-doped layer, the flat micropores were obtained (see figure 8b).
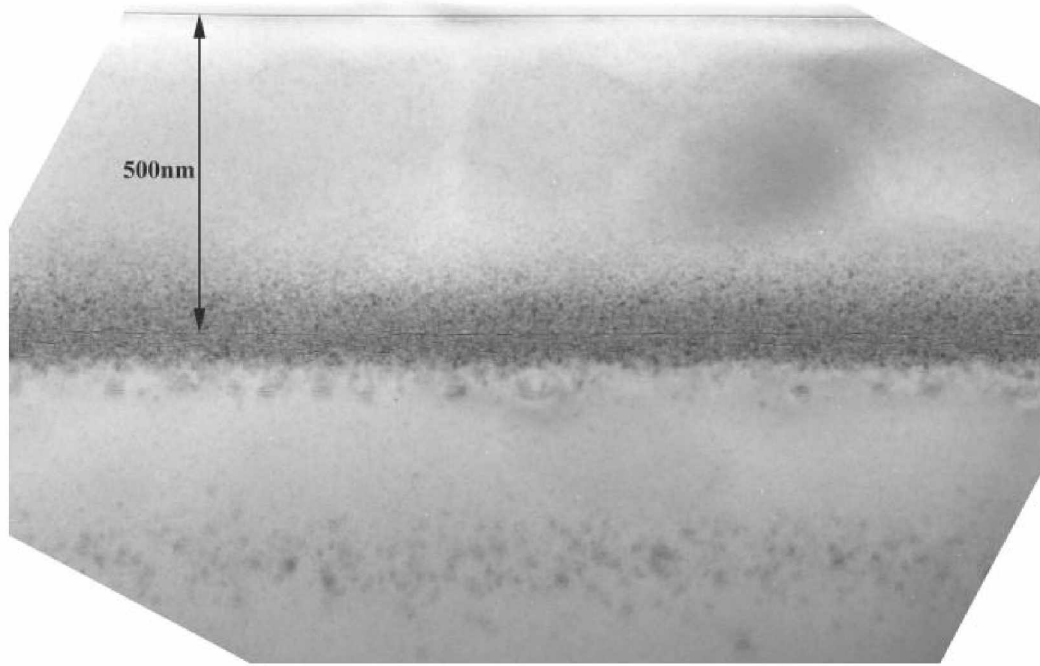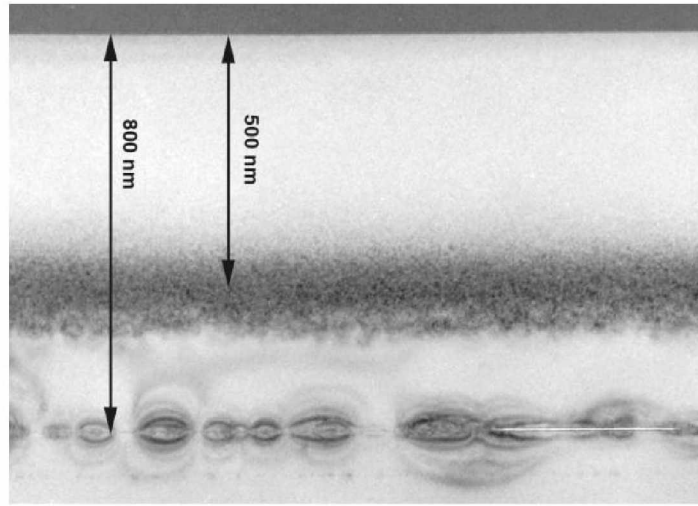
Figure 7. XTEM image of the silicon sample contained the boron delta-layer at the depth of 500 nm and implanted with 100 keV H_2^+ ions to a dose of 4×10^{16} cm^{-2}.

Evolution of microcracks within the hydrogen ion implanted region and at the area of boron delta-layer have been investigated during subsequent annealing at the temperature of 450° C. Figure 9 shows the results obtained for annealing time of 12 hours. As is indicated in the picture, two regions the microckrack growth take place.

Thus, for the purpose to produce the hydrogen traps, competitive with the real silicon surface, the interaction of hydrogen with the highly doped silicon layers has been studied as a function of a distance between the hydrogen ion range and the boron-doped region. It was obtained that boron is the effective trapping site for hydrogen and the effective nucleation center of microcracks. These processes are successful for the distance between the ion ranges and boron-doped layer up to 300 nm. These results suggest that boron delta-layers may be used for stimulation of hydrogen transfer of the thin silicon layers.

Figure 10 shows IR specters from the prisms containing the 30 nm-thick boron δ-layer with the bulk concentration of 2×10^{20} B/cm^3 presented for different annealing time in the range from 0 to 122 minutes at the temperature 400° C. A comparison between the IR specters obtained from the respective boron-doped and boron-free samples after annealing at the temperature of 400° C during 20 min is presented in figure 11. It was obtained that under these conditions, the
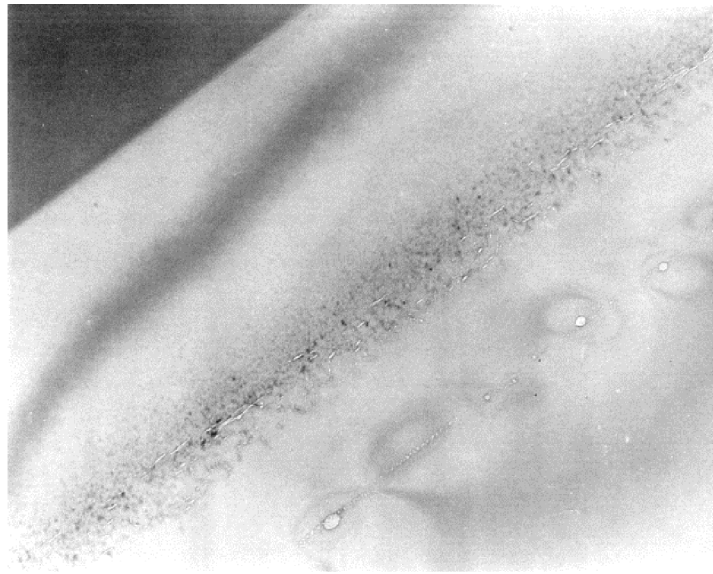
Figure 8. XTEM images of the silicon containing the boron delta-layer at the depth of 800 nm from the top surface and implanted with 100 keV H_2^+ ions to a dose of 4×10^{16} cm^{-2} for two orientations the sample. **(a)** – sample title is 0°; **(b)** - sample title is 10°.

intensity of infrared band of 2098 cm^{-1}, originated from the symmetric mode of bonded monohydrides on dimmers normal to the (2×1) {100} atomically smooth steps, is the same from the undoped prisms and from the prisms containing the boron doped layer. At the same time, in the case of the boron layer containing prisms, the intensity of the 2110 cm^{-1} infrared band, originated from the mode of hydrogen consisting platelet-like (111) defects, is by a factor of 1.5 lower than that from the undoped prisms. This means, that a density of atomically smooth (100) microcracks in the samples, containing the boron-doped layer, is not lower than that in undoped structures. The part of molecular hydrogen is higher in the boron-doped structures too.
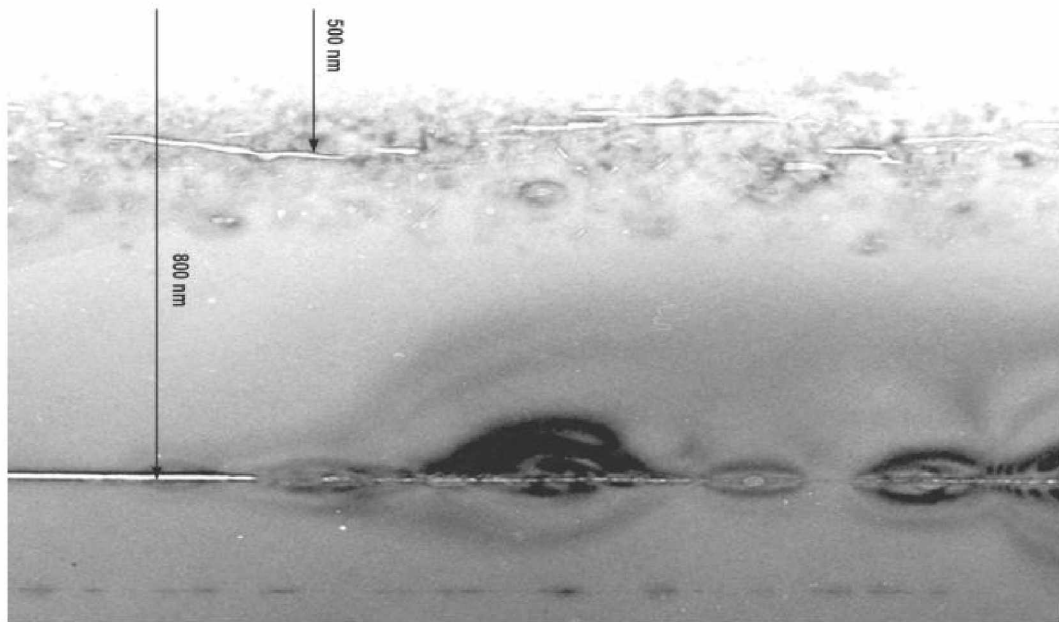
Figure 9. XTEM images of the silicon sample containing the boron delta-layer at a depth of 800 nm from the top surface after implantation of 100 keV H_2^+ ions to a dose of 4×10^{16} cm^{-2} and subsequent annealing at 450° C for 12 hours.
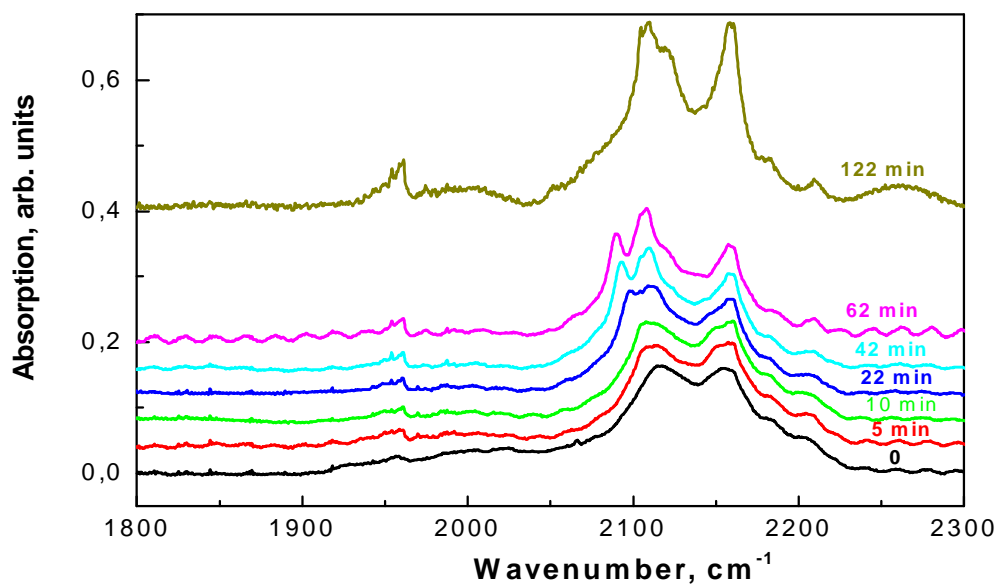

Figure 10. IR absorption specters of silicon prisms containing ultra-thin boron δ-layer as a function of annealing time at the temperature 400° C.

In the structures with the boron doped layer, a red shift of the 2098 cm^{-1} infrared band was observed when annealing time was increased from 20 to 40 minutes at the temperature of 400° C. This effect may be explained by the atomically smooth microcracks formed preferred in the deposition plane of boron atoms, which passivate one of bond in H-Si-B dimmer, which possesses lower electonegativity in comparison with that of hydrogen.
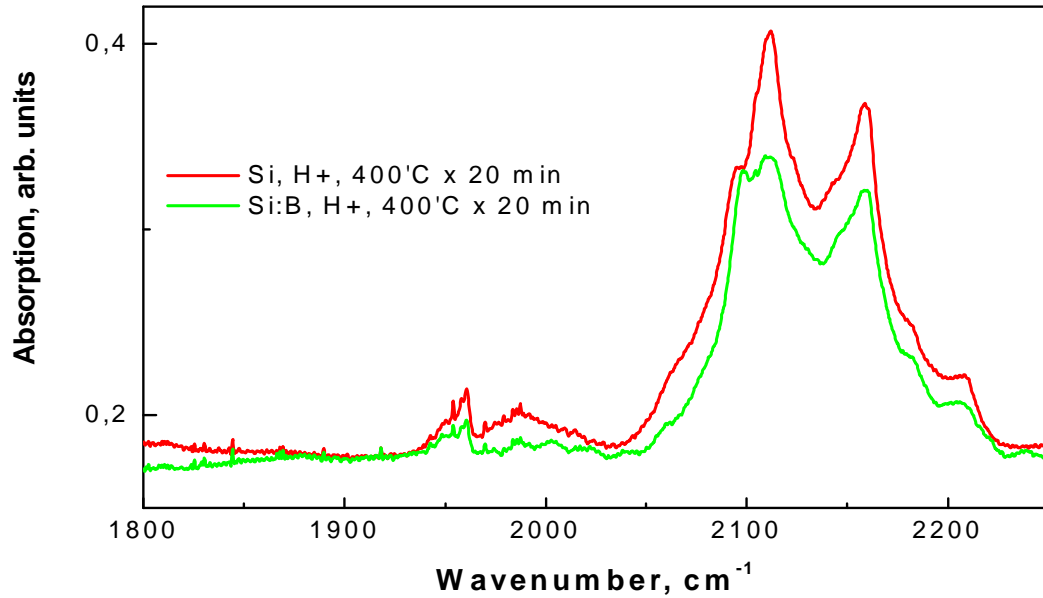

Figure 11. IR specters from the respective prisms prepared using boron-doped and boron-free silicon wafers after annealing at the temperature of 400° C during 20 min.

Arrhenius functions of the blistering and exfoliation time were investigated from pairs composed of the Si targets as well as pairs composed of boron-free silicon sample and the sample doped from boron-delta layers, respectively. Either of two used samples was implanted with hydrogen ions at an energy of 140 keV to dose of 5×10^{16} cm^{-2}. The prepared samples were annealed at the temperature ranging from 200 to 450° C during annealing time from 7 to 265 minutes. It was obtained, that the presence of boron within silicon results in decreasing in the activation energy of blistering from ~1.55 eV to ~1 eV. Under these conditions, the activation energy of exfoliation process reduced from ~1.39 eV to ~0.75 eV (see Figure 12). The results, presented in the figure 1, show that both blistering and exfoliation processes chracterized by different activation energy. This means, that mechanisms of these two processes are different.
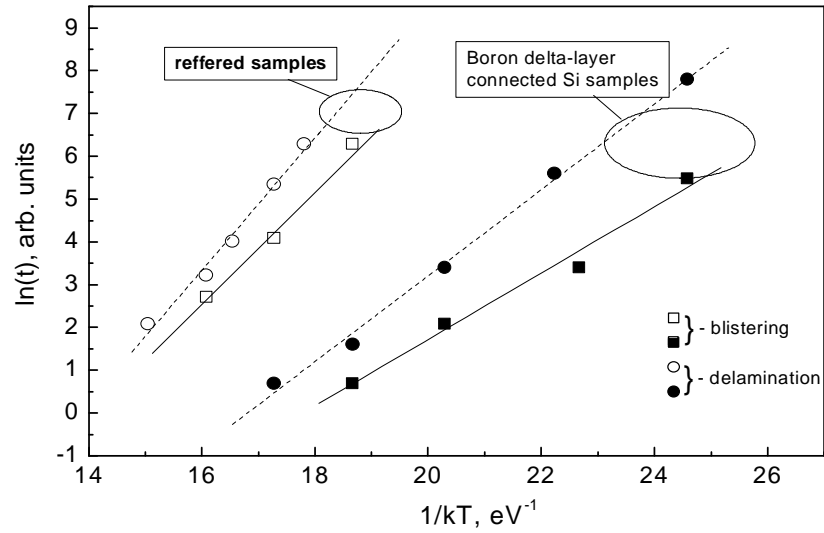
Figure 12. Arrhenius dependences of the blistering and exfoliation times for the hydrogen ion implanted Si samples with and without boron delta-layer.

<u>Task 2.</u> Transfer of thin silicon layers to different kind of substrates and study an effect of surface state and covers on the transfer process. Study of structural properties of XT and UT silicon layers.

Transfer of silicon films on silicon wafers has been studied using the samples containing boron delta-layer at the depth of 800 and 200 nm (see Task 1) from the top silicon surface. For comparison, the boron free wafers have been also used. In the case of the wafers containing boron delta layer at the depth of 800 nm, H_2^+ ions were implanted into silicon at an energy of 100 keV to dose of 4×10^{16} cm^{-2}. Ion range of 100 keV ions is of about 500 nm. Thus, a distance between the ion-implanted region and boron delta-layer amounted of 300 nm. The wafers with boron delta-layer buried at the depth of 200 nm have been implanted with 4×10^{16} cm^{-2} dose of H_2^+ ions at an energy of 40 keV. In this case, the ion range of 288 nm was provided. Taking into account a buffer silicon layer (about 75 nm), a distance between the hydrogen-ion range and boron delta-layer was of about 75 nm, respectively. In all instances, bonding and subsequent annealing at the temperature of 200° C for 2 hours in low vacuum ambient (about 10^4 Pa) resulted in low binding energy between the transferred film and base substrate. In order to increase the binding energy, the additional anneals at the temperatures of 300° C for 2 hour and 450° C up to 50 hours were carried out. No exfoliation was observed for the samples with the buried delta-layer at the depth of 800 nm. At the same time, in respective satellite wafer (without boron), the exfoliation of silicon films occurred already after 5 minutes for the same annealing

temperature. Temporary delay of the observed exfoliation process is explained by hydrogen redistribution between two layers; namely, between the ion-implanted layer and the boron-doped delta-layer. This results in decreasing of the gas pressure in micropores. Therefore, to form a main crack joining two zones of micropores, a mechanical effort has been used. In the second case, when a distance between the ion range and boron delta-layer was of about 75 nm, the exfoliation of silicon film occurred also after annealing at the temperature of 450° C for 30 minutes. However, the thickness of the transferred film was not uniform. This was two-graded. On the transferred film was observed the uniform part with the area of several tens square centimeter. Its thickness was of about 130 nm. Second part of the exfoliated layer had the thickness of about 205 nm. These two thickness magnitudes correspond to the distances of the boron delta-layer and the ion range from the top silicon surface.

In order to study the effect of the boron doped layers on the roughness of the transferred silicon films the highly doped boron layers were produced by molecular-beam epitaxy technique on the (100) oriented silicon wafers with the resistance of about 12 $\Omega \cdot$cm. First, a buffer silicon layer with the thickness of 90 nm was grown on the silicon target. Then, ultra-thin (3-4 mono-layers) boron layer with the sheet concentration ranging from 0.5×10^{15} to 1.5×10^{15} cm^{-2} was grown. The boron layer was covered with silicon film of the thickness 100-800 nm. The prepared structures were implanted with H_2^+ ions at energy ranging from 20 to 100 keV. Ion straggling was in the range from 150 to 527 nm, respectively. The roughness of the transferred films was investigated by atomic force microscopy (AFM). In the experiments, simple average roughness R_a and mean-square roughness R_q, as well as fractal parameters of the surface L_c (correlation length) and α (roughness exponent) were measured.

To determination of a root-mean-square error of the roughness degree within the scanning window L×L, statistic characterization of a surface presented in the references [6-8] was used. The root-mean-square roughness R_q of the surfaces with the dimension L×L and with the resolution of M×M pixels was determined by:

$$R_q = \sqrt{\frac{\sum_{i=1}^{M^2} h_i^2}{M^2} - \left[\frac{\sum_{i=1}^{M^2} h_i}{M}\right]^2} \tag{1}$$

where h_i is the highest image. R_q is connected with the square of the investigated surface by next expression:

$$R_q \propto \begin{cases} L^{\alpha}, \text{ for } L \ll l_x \\ w_{sat}, \text{ for } L \gg l_x \end{cases} \tag{2}$$

where $0.4<\alpha<0.9$ is roughness exponent [9], l_x is the correlation region. Expression (2) is the sequent of the surface self-similarity. The self-similar surface remains invariant under next transformation:

$$x \rightarrow bx; \quad y \rightarrow by; \quad h \rightarrow b^{\alpha}h - \tag{3}$$

A rough surface may be presented as a harmonic set:

$$h(x) = \sum_{k} e^{ikx}$$

Fourier transformation of surface geometry results in the power spectrum density I(k):

$$I(k) = \frac{1}{L}\left|\int_{0}^{L} h(x)e^{ikx}dx\right|$$

The power spectrum density as a function of roughness degree is:

$$I(k) \propto k^{-\alpha-(d+1)/2},$$

where d is dimension of Euclidean space. Figure 13 shows the correlation length l_x as a function of the roughness degree for the films with the thickness of 480 nm exfoliated under annealing temperature of 400° C from the boron free silicon wafer. In this case, root-mean-square value of the roughness was about 10-11 nm, roughness exponent α, obtained from the experiments was $\alpha=0.55\pm0.13$. This result was obtained from an ACM image with dimension of 10×10 μm^2. This result is in good agreement with that obtained from these samples by cell method. Figures 14 and 15 show the results obtained from the same structure after scanning the images with dimensions of 6.3×6.3 and 5×5 μm^2. Under conditions of decreasing scanning window, roughness exponents were obtained 0.36 ± 0.05 and 0.43 ± 0.08, respectively. This means that referred silicon surface is self-similar one. In these structures, mechanism of the micro-crack nucleation is heterogeneous with the random distribution of the nucleation centers.

Figure 16 shows an ACM image of the (100) silicon surface from the 130 nm thick film exfoliated from the boron δ-layer doped Si substrate. For the scanning window 10×10 μm^2, root-mean-square roughness value was lower than 0.2 nm. In the case of the boron δ-layer doped samples, the surface is not self-similar one, because of low surface roughness. This is close to interplanar spacing on (100) silicon surface (0.08 nm), that is lower than parasitic periodical signal. In other words, the transferred film is atomically smooth. This supposes the formation of microcavities in the planes parallel to surface of the silicon wafer. At that, the surface roughness should be dropped as the thickness of the boron-doped layer increased.
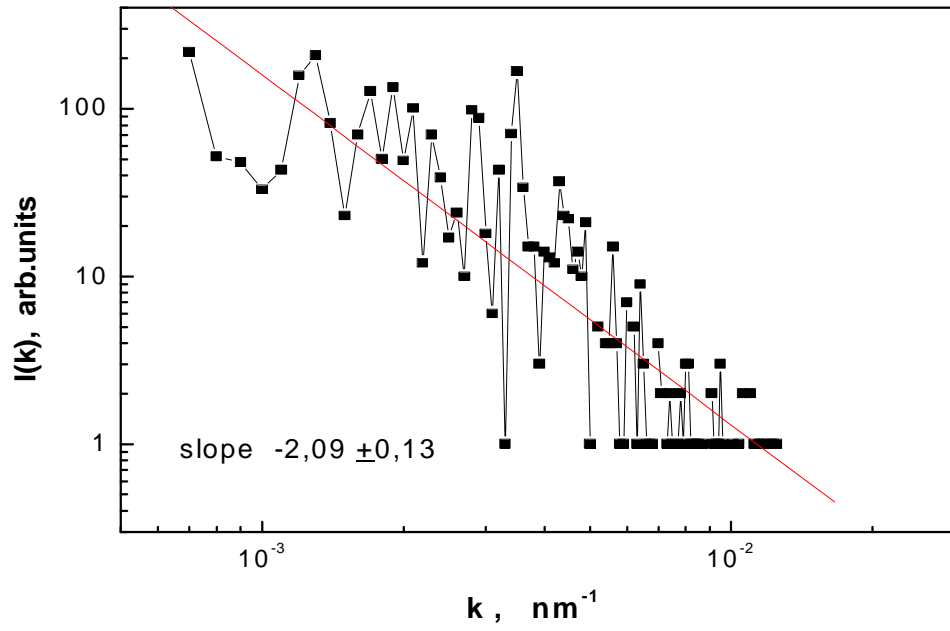
Figure 13. Surface roughness power spectrum for the 480 nm thick silicon film exfoliated under annealing temperature of 400° C from the boron free silicon wafer. Scanning window is 10×10 μm^2.

Figure 14. Surface roughness power spectrum for the 480 nm thick silicon film exfoliated under annealing temperature of 400° C from the boron free silicon wafer. Scanning window is 6.3×6.3 μm^2.
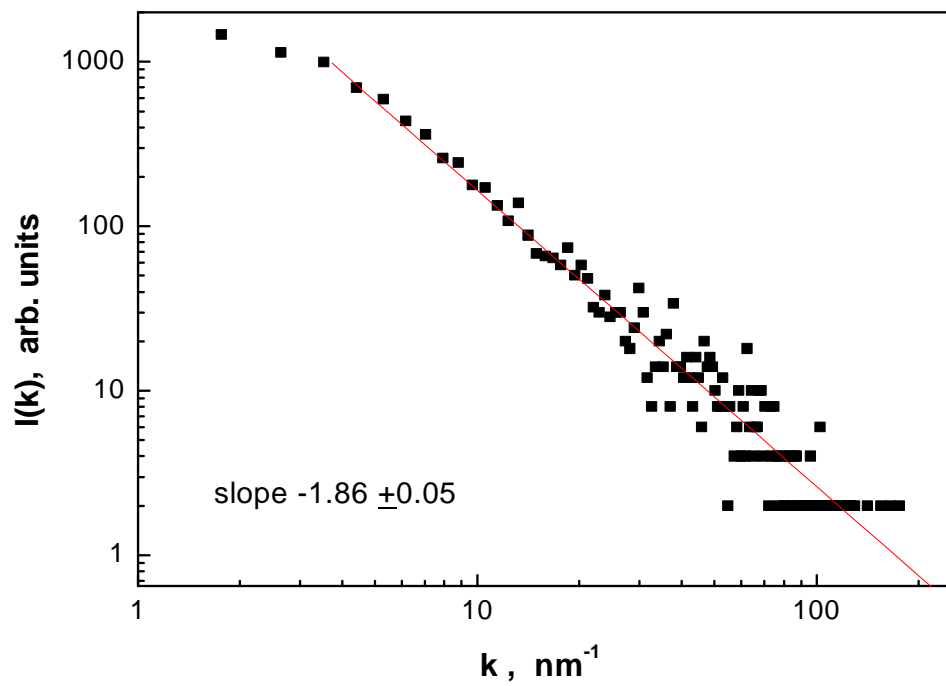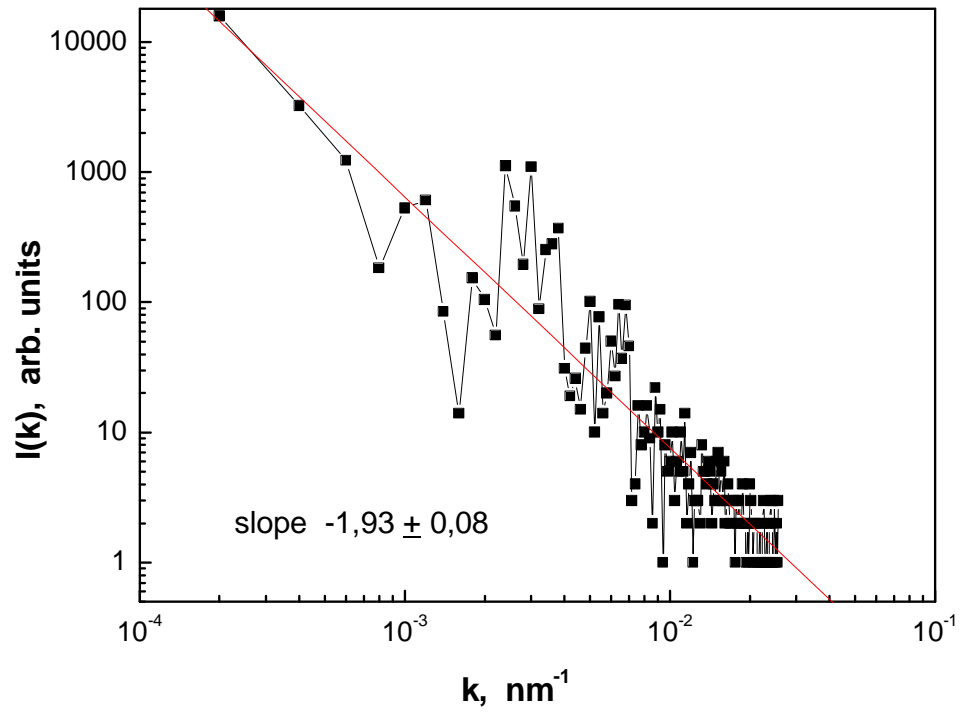
Figure 15. Surface roughness power spectrum for the 480 nm thick silicon film exfoliated under annealing temperature of 400° C from the boron free silicon wafer. Scanning window is 5×5 μm^2.
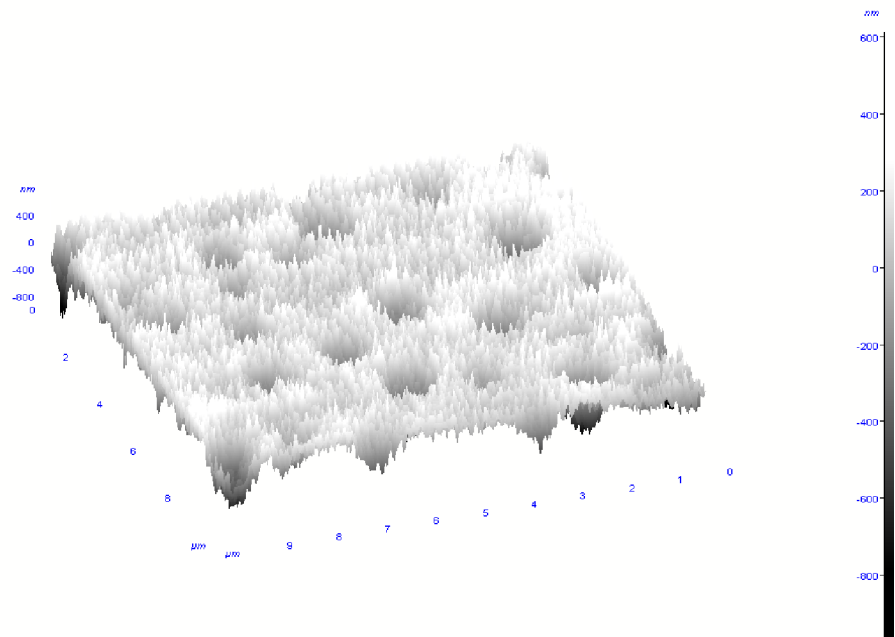

Figure 16. An ACM image of the (100) silicon surface from the 130 nm thick film exfoliated from the boron δ-layer doped Si substrate.

The obtained results shown that boron delta-layer may be used to hydrogen slicing and transfer of the thin silicon films. The obtained results suggest that buried boron delta-layers may enhance the low temperature transfer of the thin silicon layers with the small surface roughness. It has been obtained, that transfer processes from the silicon wafers containing the boron-doped layer is characterized by smaller roughness according with that from the boron-free samples.

Task 3. **Creation of model of the XT and UT Si film exfoliation in hydrogen ion implanted Si crystals.**

Hydrogen-induced splitting is a complicated hierarchical order of physical processes. To analytical modeling of these processes, a number of approximations are necessary to do. One of these is the formation of general crack from the microcrack sets developed in hydrogen ion implanted layer during subsequent annealing. In the frame of continued approximation, the relationship between the hydrogen concentration in microcrack and microcrack dimension may be obtained. Next, taking into account the hydrogen diffusion to microcrecks, the conditions of the formation of general crack by microcrac merging may be obtained. In order to describe these effects, a number of analytical methods have been developed in literature [1-9, 10-13]. The correlation between the hydrogen stimulated broken Si-Si bonds and the activation energy of splitting process was observed by Tong and Gösele [1]. Freund [2] considered the disk microcracks within the infinite elastic medium, and minimal hydrogen content to splitting activation has been estimated. Blistering of the hydrogen-filled microcracks, being at the low depth of occurrence, under the influence of anisotropic elastic forces have been investigated by Varma [3]. The thermodinamical model, in which the generation rate of hydrogen in the ion implanted layer is proportionate to ion dose, have been supposed by Han and Yu [4]. This model allows obtain the blister diameter as a function of the distance from the top surface. No hydrogen trapping by defects was taken into account. Besides the inner gas pressure, an outside force stimulated pleating process was suggested by F. Yang [5]. In Yang's model, kinetic of the molecular hydrogen formation was also proposed.

A simplified model of the formation of blisters on silicon surface has been observed also by Varma [3]. It was assumed, that hydrogen concentration in the ion-implanted region is higher than its solubility limit silicon. In this model, the implanted region has been modeled by surface with Si-H bonds weakly bonded to similar layers with substantional anisotropic voids in which H_2 agglomerates. The anisotropic growth of H_2 bubbles leads to smooth exfoliation and to the

formation of blisters. The shape of bubbles has been obtained by minimizing the free energy of the system:

$$a_0 \approx \frac{1}{4\pi} \frac{3\kappa_B T N_0}{\gamma - \frac{3}{4}\rho_S \kappa_B T f(T) \ln(\frac{3T N_0}{4\pi\gamma})}, \qquad (1)$$

$$h \approx (\frac{ND\kappa_B T}{t})^{1/2}, \quad a_0 \gg t \qquad (2)$$

$$h \approx (\frac{ND\kappa_B T}{a_0})^{1/2}, \quad a_0 \ll t \qquad (3)$$

where $N = N_0 + \rho_S(\pi r_0^2)f(T)$ is the number of molecules in the bubble; γ is the energy of interaction of hydrogen atom with the surface of microcavity; T is annealing temperature; N_0 is the concentration of hydrogen molecules within the microcavity at zero temperature; k is Boltzmann constant; ρ_S is the hydrogen atom density on the microcavity surface; $D \approx (1-\nu)/E$, where E is the Young's modulus, ν is Poisson ration; $f(T) = \exp(\frac{-\Delta}{\kappa_B T})$ is the termodinamical fraction which comes off the walls; Δ is a difference between the energy of hydrogen molecule and the energy of two separated hydrogen atoms on the microcavity surface. The formation of extensive microcracks occurs under condition of $a_0 \to \infty$. From this, it follows that the exfoliation temperature may be expressed by

$$\kappa_B T_e f(T_e) \ln(\frac{3T_e N_0}{4\pi\gamma}) \approx \frac{3}{4}\gamma / \rho_S \qquad (4)$$

In this model, the height of microcavity is not dependent on its radius a_0 and on the depth of occurrence of microcavity. The ratio of the typical microcrack height to its radius is one over for both small and large microcracks. It means, that this model includes no exfoliation evidences.

The grave disadvantage of the analyzed models is the representation of the ion implanted silicon by isotropic elastic medium [10]. In these models, the radiation defect penetration is provided by the anisotropic properties only. This results in the biaxial compression intrinsical to the ion implanted silicon layers, and in the expanding pressure normal directed to the surface-plane. However, as it should be from experimental, the preferential directions exist in the splitting plane. These are due to a motion of general crack front.

There are two different point of view on the formation of microcracks in hydrogen-ion implanted silicon. First, as process of the formation and next interaction of a large number of small microcracks. Second, as the fabrication of screening and antiscreenning dislocations with following bilding the microtwins by the generation of basis and closing dislocations.

A.A. Griffith [10] solved a problem on the propagation and amalgamation of the cracks in the anisotropic brittle solid. He has proposed an equation to obtain the critical pressure within the cracks with two inner surfaces of the surface energy γ_s:

$$\sigma_c = (\frac{2E\gamma_s}{\pi a})^{1/2} \qquad (5)$$

This equation has been generalized by G. R. Irwin [11] to the dissipation energy of plastic deformation. Amplitude of the local stresses around the microcrack front has been determined by the pressure intensity factor K:

$$K = \sigma \cdot \sqrt{\pi \cdot a} \cdot f\left(\frac{a}{w}\right) \qquad (6)$$

where σ is the external pressure; a is the crack length; f(a/w) is correction factor depending on the sample and crack geometry. Today, analytical solution exists for two parallel cracks in the infinite two-dimensional wafer only. Numerical analysis shows [12, 13] that in the case of two co-planar microcracks, the repulsive interaction takes place. This has to prevent from its coagulation. The presented analysis shows that the exfoliation process demands of the detail investigation.

Theoretical analysis of the boron effect on the silicon film exfoliation has been carried out. It was obtained that boron atoms stimulate the formation of H_2^+ molecules because of decreasing both of the dangling bonds density on the (100) silicon surface and of the binding energy of Si-H pairs. Variation of the hydrogen binding energy depends on the boron concentration and change from 0.4 eV to –0.4 eV as the surface boron concentration increases from 3.4×10^{14} cm^{-2} (1 monolayer) to 6.8×10^{14} cm^{-2} (2 monolayers). This results in the growth of hydrogen gas pressure within micropores. As result, the enhancement of the exfoliation takes place. At the same time, exfoliation process is dependent on the thickness of the boron-doped layer. It was shown, that in the case of the boron-doped layer with the thickness lower than 2 nm, the formation of H_2^+ molecules may lead to the repulsion of the neighbor micropores in the plane of delta-layer. Under these conditions, exfoliation process is delayed.

Crystallographycal limit for the thickness of the transferred silicon layer has been obtained. In the case of the {111} oriented silicon planes, this limit is equal to 1 doubled monolayer; in the case of the {100} oriented silicon planes, it is 2 monolayers.

Task 5. Investigation of electrically active and structural defects in strained layers.

In order to investigate the electrical properties of the thin silicon films, these were transferred on thermally oxidized silicon substrates. The thickness of the films d_{Si} was varied from 9 to 55 nm. In the experiments, p-type layers with the hole concentration N_D of 10^{17} and 10^{19} cm^{-3} and n-type silicon layers with the electron concentration N_A of 10^{18} and 10^{19} cm^{-3} were prepared. To study the electrical properties of the exfoliated silicon films, MOS structures have been prepared. During investigations of the current-voltage characteristic, the carriers were injected into thin silicon films by bias applied to silicon substrate. Figure 17 demonstrates the drain-source current-voltage characteristics of the transistors as a function of the substrate bias for the transferred films with different thickness and doping level.

Figure 17. Drain-source current-voltage characteristics of the transistors as a function of the substrate bias for the transferred films with different thickness and doping level: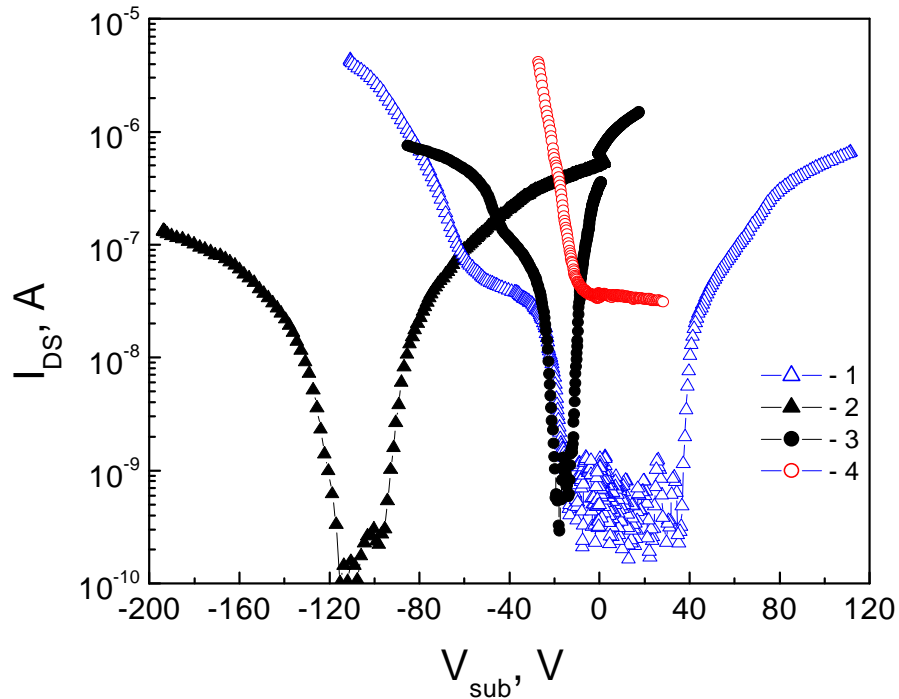 1 - d_{Si} = 9 nm, N_D = 2×10^{19} cm^{-3}; 2 - d_{Si} = 20 nm, N_D = 10^{19} cm^{-3}; 3 - d_{Si} = 44 nm, N_D = 10^{17} cm^{-3}; d_{Si} = 55 nm, N_D = 10^{18} cm^{-3}.

It was obtained that under substrate bias $V_s = 0$, the top thin silicon layer may be non-conductive, nevertheless the doping level was high. It is a sequent of positive charge in silicon dioxide. Because of this positive charge, the conductivity of the top n-type silicon films is provided both by quasi-neutral bulk and by the thick interface charge. At the same time, conductivity of the p-type layer is provided by the layer thickness reduced by the depletion region near the interface. In the case of the comparable thickness of the depletion layers and the transferred film, the conductivity tends to zero. From this, it was concluded that n-type thin silicon films are more preferable regarding electrical applications than those of the p-type conductivity.

Conclusions.

The effect of boron on nucleation of hydrogen micropores and splitting of silicon layers was studied. Two kinds of boron doping have been used in these experiments. Namely, they are boron ion implantation and diffusion from boron delta-layers grown by MBE technique. It was shown, that highly boron doped silicon layers contain the heterogeneous nucleation centers of high density. Boron is an effective trap for hydrogen and an effective nucleation center of micropores. Presence of boron within silicon results in decreasing in the activation energy of blistering process from ~1.55 eV to ~1 eV. Activation energy of exfoliation process reduced from ~1.39 eV to ~0.75 eV. The results suggest that blistering and exfoliation processes characterized by different microscopic mechanisms.

It was obtained that buried boron delta-layers may enhance the low temperature transfer of the thin silicon layers with the small surface roughness. This is caused by the formation of microcavities in the planes parallel to surface of the silicon wafer. It was shown, that the surface roughness is decreased as the thickness of boron-doped layer is diminished. Analysis of ACM images of the boron-free layers shows that its surface is self-similar one. In these structures, mechanism of the micro-crack nucleation is heterogeneous with the random distribution of the nucleation centers. In the case of the highly boron-doped films, its surface is not self-similar one. This is atomically smooth.

From theoretical analysis, a crystallographycal limit for the thickness of the transferred silicon layer was obtained. In the case of the {111} oriented silicon planes, this limit is equal to 1 doubled monolayer; in the case of the {100} oriented silicon planes, it is 2 monolayers.

Electrical properties of the transferred silicon films as a function of its thickness and doping level were investigated. It was concluded that n-type thin silicon films are more preferable regarding electrical applications than those of the p-type conductivity.

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